CONCEPTUAL PLANS FOR PRODUCING DATA PRODUCTS FROM THE MODERATE RESOLUTION IMAGING SPECTROMETER (MODIS)

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Abstract--The Moderate Resolution Imaging Spectrometer (MODIS) has been designated as a facility instrument on the first NASA polar orbiting platform as part of the Earth Observing System (EOS) and scheduled for launch in the late-1990's. The near global daily coverage of the MODIS, combined with its continuous operation, broad spectral coverage, and relatively high spatial resolution, make it central to the objectives of EOS. The mission requirements of the EOS and the MODIS instruments may be traced through the MODIS science team members to the proposed set of at-launch MODIS data products. The development, implementation, production, and validation of these at-launch data products defines a set of functional, performance, and operational requirements on the data system, that operates between the sensor measurements and the data products supplied to the user community. In this paper, we review the science requirements guiding the processing of MODIS data, and discuss conceptual plans for the production of data products from MODIS for use by the scientific community. Key words: MODIS, EOS, EOSDIS, Data Systems, Remote Sensing, Global Change.

INTRODUCTION

The goal of the Earth Observing System (EOS) Mission is to understand changes of the Earth, viewed as a completely integrated system, by examining the Earth's hydrological, geophysical, and climatic processes coupled with the biogeochemical cycles [1]. To achieve this goal, long-term multidisciplinary Earth observations must be made. One of the instruments proposed to measure oceanographic, terrestrial, and atmospheric parameters is the Moderate Resolution Imaging Spectrometer (MODIS) [2,3]. MODIS will observe nearly the whole Earth twice a day; once during daytime and once during nighttime. Current plans call for the collection of data for at least 15 years, thus providing long-term global data sets to the scientific community for the study of global change. MODIS will be composed of two cross-track scanning components: nadir-viewing MODIS-N [4] and tiltable MODIS-T [5]. MODIS-N will observe the visible, near-infrared, and thermal-infrared spectral regions over 36 spectral bands. Observations will be taken at spatial resolutions ranging from 214 to 856 meters at nadir. MODIS-T will have a nadir resolution of 1.1 km and observe from 410 to 875 nm in 32 bands, each between 10 and 15 nm in width.

MODIS AT-LAUNCH PRODUCT GENERATION

The data processing system supporting MODIS, which includes the EOS Data and Information System (EOSDIS), is being developed to accommodate the development and implementation of both at-launch and future data product algorithms [6,7]. Here, we will concentrate primarily on the conceptual plans for producing the at-launch products.

RADIANCE DATA PRODUCTS

The general science community has an interest in both radiances at the top of the atmosphere and at the bottom of the atmosphere. The EOS-wide requirement for MODIS radiances is presumed to extend over most of the spectral bands (particularly in the reflected wavelengths). The requirement will include calibrated and navigated radiances at both the top and bottom of the atmosphere (Figure 1).

Several MODIS-N water-leaving radiance bands may be required for general oceanographic use; however, water-leaving radiances from most of the MODIS-T spectral regions will be required for algorithm development work. Also, additional longer wavelengths not required for open ocean may be required for this product for coastal regions. These bands are divided into those requiring atmospheric correction to produce water-leaving radiances and those requiring water vapor correction to produce sea surface temperatures. The sea ice algorithms should require no atmospheric correction, and utilize bands used for other ocean products.

MODIS-T radiances are relevant to the estimation of water-leaving radiances and products derived therefrom. All bands in the visible wavelengths will probably be used for research, even if they are not required for at-launch data products. Thus, MODIS-T may require atmospheric correction for all bands between 400 and 700 nm, and perhaps to 875 nm.

In research involving the remote sensing of terrestrial vegetation, many results have been presented in a qualitative way (e.g., ratios of reflectance and correlations of the ratios with ground data). Using the greater multispectral capabilities and higher bit quantization of MODIS, it will be possible to advance to the quantitative analysis of remotely sensed vegetation dynamics using atmospherically corrected radiances. For the terrestrial sciences, a number of MODIS-N bands may therefore be routinely corrected for atmospheric effects.

OCEAN DATA PRODUCTS

Derivation of MODIS ocean data products begins with the calibrated and navigated radiances. If pixels pass the cloud filter, they should then be used, uncorrected for atmosphere, to determine sea-ice extent. They can also be corrected for water vapor to determine the sea surface temperature. These products can only be generated by MODIS-N because they require observations in thermal-infrared wavelengths. Otherwise, the pixels will be atmospherically corrected to produce water-leaving radiances. At this time, it is expected that both MODIS-N and -T will generate water-leaving radiances and products derived therefrom. Although this scenario involves some duplication, it also maximizes global

MODIS-N AND MODIS-T STANDARD (AT-LAUNCH) PROCESSING SCENARIO

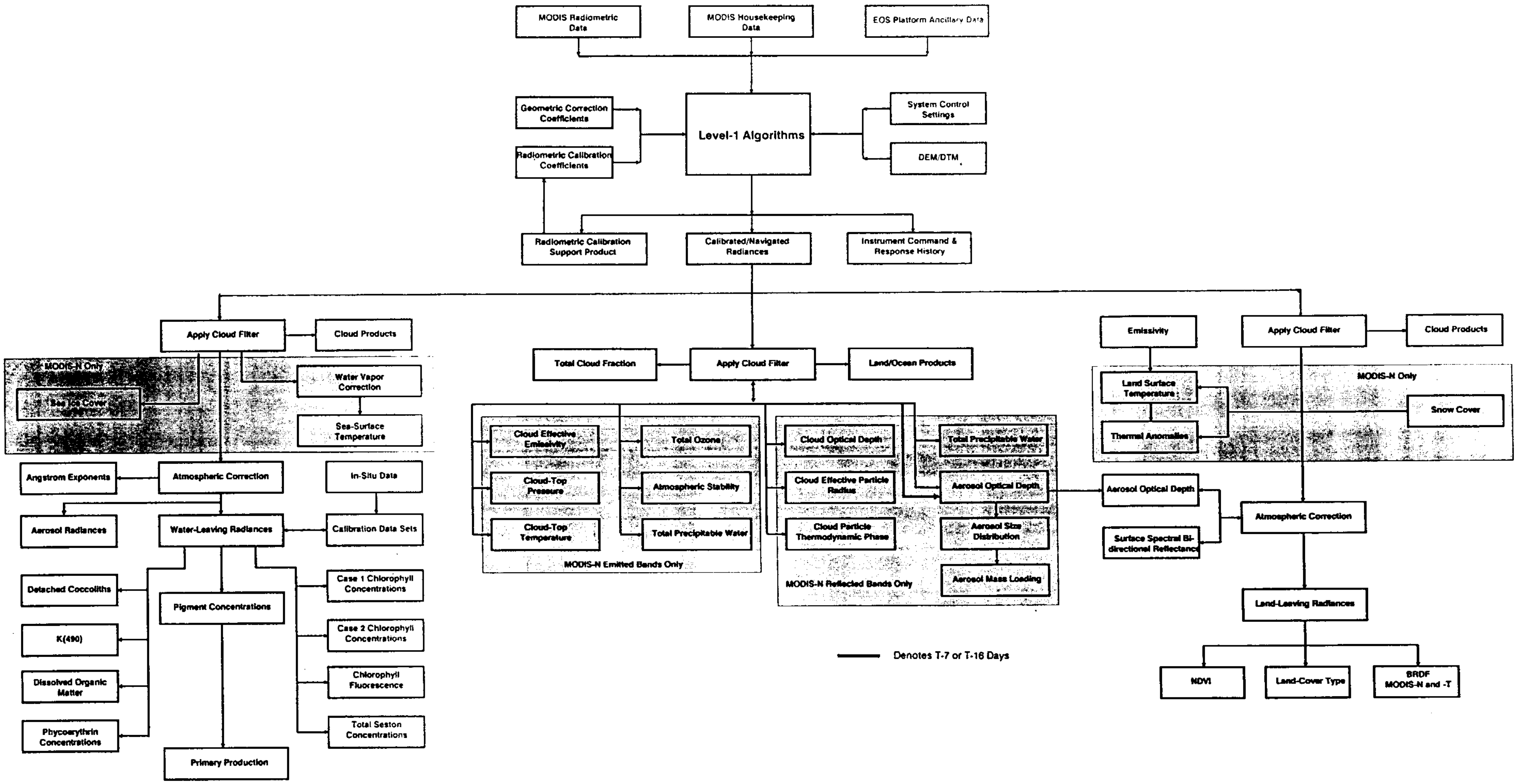

Figure 1. Conceptual data flows through the MODIS at-launch processing illustrating: (1) the Earth location and calibration data flows and the merging of MODIS radiometric and housekeeping data and platform ancillary data; (2) the application of the cloud filter; and (3) the ocean, land, and atmospheric discipline data processing scenarios.

coverage by allowing MODIS-N to fill gaps in MODIS-T observations and vice versa.

The atmospheric correction involves determining the Rayleigh scattering and aerosol absorption and scattering contributions to the total radiances, and removing them. Angstrom exponents, an indicator of the wavelength dependence of aerosol attenuation, come out directly in this process. Atmospheric correction will directly generate two ocean at-launch products: water-leaving radiances and aerosol radiances. Water-leaving radiances form the foundation for the remaining products. They would be used to directly obtain pigment concentrations and chlorophyll-a pigment concentrations for Case-1 and Case-2 waters. In the generation of Case-2 pigment concentrations, a flag differentiating Case-1 from Case-2 areas will be used to determine whether to employ the Case-2 algorithm. Also derived from the water-leaving radiances are chlorophyll fluorescence, total seston (suspended particulate matter) concentrations, detached coccolith concentrations, K(490), dissolved organic matter and phycoerythrin concentrations. Phycoerythrin is an accessory light-harvesting pigment present in specialized types of phytoplankton.

For the oceanic primary production, an empirical approach relates MODIS-generated pigment concentrations to measured in-situ primary production. Surface incident PAR and the diffuse attenuation coefficient for PAR, as well as Case-1 and Case-2 chlorophyll-a concentrations, may also be involved in this algorithm. Chlorophyll fluorescence is also envisioned as a possible method to obtain primary production in the future.

Cloud products may then be used to make determinations of surface incident Photosynthetically Available Radiation (PAR).

ATMOSPHERIC DATA PRODUCTS

One of the first steps in the atmospheric MODIS product generation will be the setting of cloud cover flags. We anticipate that cloud flags will be set in a two-step process. First, a series of tests will be performed to identify clear fields of view. Second, a series of tests will be applied to separate homogeneous clouds from partly cloudy and mixed IFOVs. Snow and ice cover discrimination will also be performed at this stage of the processing. A cloud fractional area product can be produced directly from the cloud flags.

A series of tests for cloud cover can be performed, and the result of each test would be stored by setting flags. Every test could be applied to each pixel, and the result of up to eight tests can be carried as a single byte. This technique allows MODIS data users flexibility in selecting data for further processing. This procedure is viewed as necessary since there is no single definition of a cloud, and certain types of cloud cover may not prevent the determination of surface properties. For example, NDVI may be useful even under thin cirrus. Cloud flags will be useful for users of either MODIS-N or -T radiances. However, only MODIS-N radiances will be required to generate atmospheric at-launch data products.

Those observations for which cloud flags have been set will be processed to retrieve cloud data products. Infrared radiances from as many as 16 bands may be used to determine cloud-top pressure and temperature by means of a CO_2 slicing algorithm and effective cloud emissivity. Radiances from up to five MODIS-N reflected bands will be used to retrieve cloud thermodynamic phase, optical depth at $0.66\mu m$, and effective particle radius. Surface reflectances for these bands will be required as ancillary data.

The infrared radiances will also be used for all scenes to compute the total ozone, atmospheric stability (e.g., lifted index), and total precipitable water. Layer-mean temperatures and water vapor amounts will be byproducts in the generation of these at-launch products. Observed or forecast surface and atmospheric temperatures will be required as ancillary data.

All of the processing to this point can be done for a single swath of MODIS-N data (one scan). Some of the products may require the combination of scan swaths so that the analysis can be applied over larger areas. In particular, the algorithms which would be developed to determine cloud area and perimeter, fractional cloud coverage, and aerosol parameters may work most efficiently with scenes with dimensions of 200 km or larger.

Required inputs to the aerosol at-launch data product processing include Level-1B radiances over approximately eight spectral bands, previously observed radiances for scenes with the same viewing geometry (perhaps 7 or 16 days earlier), NDVI values, land-cover type maps, total column ozone amounts, total precipitable water, and surface relative humidity. The radiances will first be screened to remove clouds. Depending upon the surface type, aerosol optical depth (0.41 to 2.13 μm) could be calculated by as many as three different algorithms. Surface spectral reflectances or albedos would also be required by some of these algorithms. Given aerosol optical depths, the aerosol size distribution and aerosol mass loading then become derivative data products.

LAND DATA PRODUCTS

Except for aerosol optical depth and spectral surface albedo, the land at-launch data product processing scheme shown in Figure 1 assumes that all atmospheric computations required to support land product processing are done as a part of atmospheric processing. Since aerosol optical depth and surface spectral albedo both affect the radiance observed by the MODIS instruments, they appear as simultaneous unknowns in the solution process, and surface spectral bidirectional reflectance is obtained automatically as a coproduct of atmospheric correction. Surface spectral albedo might be computed in the final stage of atmospheric processing just before dedicated land processing begins.

The atmospherically corrected radiances serve as inputs for the determination of land surface temperatures, thermal anomalies, snow/ice cover, vegetation indices, land-cover type, and the development of bidirectional reflectance distribution functions. Since thermal anomalies, such as fires and volcanic eruptions, may affect the apparent value of the land surface temperature, thermal anomaly events may need to be tagged in the listings of land surface temperature. Similarly, extraordinary values of land surface temperatures may help to corroborate thermal anomaly events, so that the land surface temperature may be examined as a part of the thermal anomaly identification process. The snow/ice identification makes use of land temperature determinations, as well as reflected visible and near-infrared radiance observations.

KEY MODIS UTILITY ALGORITHMS

The algorithms for the at-launch geophysical data products will be provided by the MODIS Science Team Members. There are a number of algorithms, other than the at-launch geophysical algorithms, which appear essential to the reduction of the Level-0 MODIS data and the successful generation of higher-level products, including standard algorithms for: calibration, earth location, topographic correction, cloud identification, cloud and snow/ice discrimination, atmospheric correction, time and space averaging and rectifying/overlaying, and display and processing.

Calibration Algorithms--To support the scientific goals of EOS and the MODIS science team members, the maintenance of the MODIS calibration over the planned 15-year period will be an area of substantial emphasis for the science team. Calibration may be performed by a MODIS Instrument Characterization Team (ICT), which would be composed of MODIS science team members and supporting staff. The ICT should fully characterize the MODIS-N and -T instruments and also consider the absolute MODIS calibration and, perhaps, most importantly from a perspective of global change, the relative calibration stability of MODIS over time. Pre-flight calibration data, instrument models and simulated data, on-board calibration data, routine data, data taken over ground-truth sites, and supporting ancillary and in-situ data would be used by the ICT. The ICT is to be responsible for the delivery of sensor calibration algorithms and coefficients to the CDHF so that MODIS data products may be generated. For this purpose, the calibration algorithms would include: instrument data monitoring, analysis of internal calibration data (potential sources include blackbodies, lamps, space, and the sun and moon), analysis of instrument models, comparison to in-situ and ground-truth data, comparisons to other EOS and non-EOS instrument data, intercomparisons of MODIS-N and MODIS-T collocated, coincident, and co-angular data sets, and assignment of the MODIS production calibration coefficients.

Earth Location Algorithms--The navigation of MODIS observations to the Earth's surface is required. At nadir, positioning accuracies of at least 500 m (i.e., about one-half pixel) are estimated to be necessary to meet the science requirements. To accomplish this task, the Earth location algorithms will include: determination of the sensor IFOV line of sight (given platform position and attitude, platform thermal or dynamic distortion data, and sensor tilt and scan angles), navigation of the IFOV centers to the earth geoid, correction for the effects of atmospheric refraction (a small but systematic effect), interpolation of the earth locations from a sparse array of anchor points to each IFOV, and correction for surface topography.

Topographic Corrections for MODIS--A global Digital Elevation or Terrain Model (DEM/DTM) is highly desirable for the generation of standard data products. Applications of the DEM include (Jan-Peter Muller, personal communication): correction of geometric distortion (pixel shifts during navigation; orthographic resampling), radiometric correction for terrain slope and aspect, as well as shadowing from sub-pixel scale features, atmospheric correction for path radiance and thermal profiles, and surface roughness.

Present analyses indicate that a global DEM, with a spatial resolution and vertical accuracy approaching 100 m and 10 m respectively, is necessary. The DEM might be routinely applied to all pixels located in regions of the Earth for which the terrain elevation exceeds 1 km.

Cloud Identification Algorithms--For the analysis and retrieval of data products at the Earth's surface, it will be necessary to identify the presence of clouds. The at-launch cloud product algorithms should be more sophisticated than those required to make a yes/no decision regarding cloud cover. There are a substantial number of techniques available that could possibly be used for the identification of cloud cover. The MODIS instruments, and particularly MODIS-N, offer a wide spectral capability for cloud detection. Because many of the Level-2 data product algorithms will have a heritage that is distinct and unique from the other product algorithms, it will probably be appropriate to employ multiple (parallel) cloud detection algorithms. A set of flags (from six to ten) could be set based on the detection technique (e.g., IR threshold, VIS reflectance, spectral flatness, spatial coherence, bispectral, maximum likelihood, etc.). Each higher-level algorithm would then be free to accept or reject observations based on consistent definitions of cloud contamination appropriate to that algorithm. In addition to cloud identification and cloud versus snow/ice discrimination algorithms, it may be desirable to delineate cloud shadows where possible.

Atmospheric Correction Algorithms;-For the analysis and retrieval of data products at the Earth's surface, and particularly for oceanic product retrievals, which provide only a small contribution to the total reflected radiance signal, it is essential that the atmospheric "contamination" be removed. Atmospheric correction over land surfaces is also critical. The development, refinement, and implementation of atmospheric correction algorithms may be a major research activity, particularly for aerosol estimation and correction. Furthermore, maximum commonality in the atmospheric correction procedures over land and ocean surfaces should be considered, so that artificial discontinuities at coastlines are not introduced. Clear sky contamination sources include: Rayleigh scattering, aerosols, ozone, and total precipitable water.

Time and Space Averaging Algorithms--Standard algorithms averaging product data to standard MODIS grids may be required. Several different compositing methods may be employed depending on the particular product. These might include averages of densely or sparsely sampled parameters, selection of a single or several pixels within a region to represent the whole, pixel intervals (e.g., every second, third, or fourth pixel in time or space), empirical orthogonal functions (EOFs), or low/high/ band-pass filters. The different techniques (which will produce such diverse products as NDVI, sea surface temperature, ocean bio-optical constituents, and cloud parameters) must be self-consistent to enable the study of the Earth as a system.

Other algorithms will be required to remove the effects of bidirectional anisotropy in the measured radiance field, limb darkening, and the dependence of albedo on solar zenith angle. The development of algorithms that can overlay observations taken from different viewing angles (side-to-side and fore-to-aft) with varying footprint sizes is required. Many products will require weekly, monthly, seasonal, and annual averages.

ANCILLARY DATA REQUIREMENTS AND ACQUISITION

Ancillary data sets will be required to generate both at-launch and research and development MODIS data products. These data sets must be acquired, supplied, or otherwise made available by the EOSDIS. The availability and timeliness of required ancillary data must be considered in the design of the data systems supporting MODIS. For example, National Meteorological Center (NMC) global gridded fields of surface pressure and 1000 mb winds must be supplied within 24 hours of MODIS observation. In situ data, including optical and other buoy measurements, surface and upper-air meteorological observations, and other data types, must also be made available within 48 hours for the quality assessment or validation of data products prior to archival and distribution.

Some MODIS products may require ancillary data from other EOS instruments (e.g., AIRS tropospheric and surface temperature fields or profiles). These data must be available in a sufficiently timely fashion to meet established requirements.

Another complication to the design of the processing system is the fact that certain MODIS geophysical product algorithms may require ancillary data products which are produced using MODIS data (such as with the atmospheric correction over land). It will be important to identify these data dependencies within the MODIS processing system and EOS as a mission, and to ensure that no conflicts arise due to the ancillary data requirements of multiple algorithms or instruments.

A substantial number of other correlative data sets will also be required for the development and validation of future MODIS data products. These will include, for example, data from SPOT, aircraft measurements, and other US, Japanese, and ESA instruments.

A COMPLETE MODIS SYSTEM SIMULATION

To support the integration, testing, and optimization of software to generate MODIS data products prior to launch, it will be essential that a realistic and comprehensive simulated MODIS data set be generated. This class of system simulation will include the following six steps: formulation of a definition of the Earth's description, collection of geophysical parameter data, creation of a robust forward model for the generation of spectral radiances, creation of orbital and instrument models, introduction of anomalies, noise, and errors into the measurements, and the simulated measurement of radiances and creation of the instrument data packets.

When the Earth definition is formulated, the physics must include a radiatively consistent treatment of the effects of each of the proposed core products. The geophysical parameter data requirements will flow from the Earth description, and will include fields of clouds fraction, ozone, surface pressure and wind speed, vegetation, and surface temperature to name just a few. Global, multi-day (e.g., full 16-day orbital repeat period) domains for the summer and winter seasons should be considered.

It is envisioned that perhaps three increasingly complete implementations of MODIS at-launch product generation code prototypes be made. These might be delivered at three, two, and one years prior to launch. The implemented code, the processing capacity of EOSDIS, and even the robustness of the retrieval algorithms (i.e., the capability for exception handling) could then be exercised through application of the simulated MODIS data. For each pass, the simulated MODIS data could be made incrementally more comprehensive and realistic. Given an adequate description of the characteristics of the Earth, the MODIS instrument, and the EOS platform, successful operation of the MODIS at-launch processing software on the final simulated data set would provide the MODIS and EOS science communities with the closest possible approach to a guarantee of standard data product generation shortly after launch.

CONCLUDING REMARKS

When MODIS data product software prototyping is considered, each of these algorithms and their related code may be visualized and realized as a separate module. The calling sequence for the modules will be similar or identical to the scenarios illustrated in Figure 1, with one exception. The calibration coefficients, and the calibration adjustments generated through a comparison of the atmospherically corrected radiances and in-situ data, will likely require human intervention. The improved calibrations will be applied to adjust the radiance values, either for future processing or for reprocessing. The time scale for this step could be from weeks to months initially, and then from months to annual well after launch.

Parallel and vector architectures will be considered for EOSDIS to accommodate the massive processing load imposed by the combination of sophisticated geophysical parameter retrieval algorithms and a high data rate. In any MODIS scan, the viewing swath may include observations of open ocean, coastal regions, clear land, cloudy regions, and possibly snow and sea-ice cover. To be permit efficient processing, the integrated MODIS processing code must be optimized to handle a wide variety of scene type mixtures.

Changes to the preliminary processing concepts presented here are expected between now and launch. The alterations may result from improved or future algorithms, and may be realized as alternative at-launch products, or as future implementations of post-launch products. The flight of the Sea Wide Field of View Sensor (SeaWiFS) instrument, for example, may result in some changes.

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